PCT

(51) International Patent Classification 6 :		(11) International Publication Number: **WO 99/46558**
G01B 11/30	A1	(43) International Publication Date: 16 September 1999 (16.09.99)

(21) International Application Number: PCT/US99/05189

(22) International Filing Date: 10 March 1999 (10.03.99)

(30) Priority Data:
09/037,806   10 March 1998 (10.03.98)   US

(71) Applicant: VLSI STANDARDS, INC. [US/US]; 3087 North First Street, San Jose, CA 95134 (US).

(72) Inventors: SCHEER, Bradley, W.; 1495 Teresita Drive, San Jose, CA 95129 (US). PROCHAZKA, J., Jerry; 5019 Raven Way, Clayton, CA 94517 (US).

(74) Agent: SCHNECK, Thomas; Law Offices of Thomas Schneck, P.O. Box 2-E, San Jose, CA 95109–0005 (US).

(81) Designated States: JP, KR, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: ATOMIC–LEVEL STEP–HEIGHT STANDARD CERTIFICATION METHOD
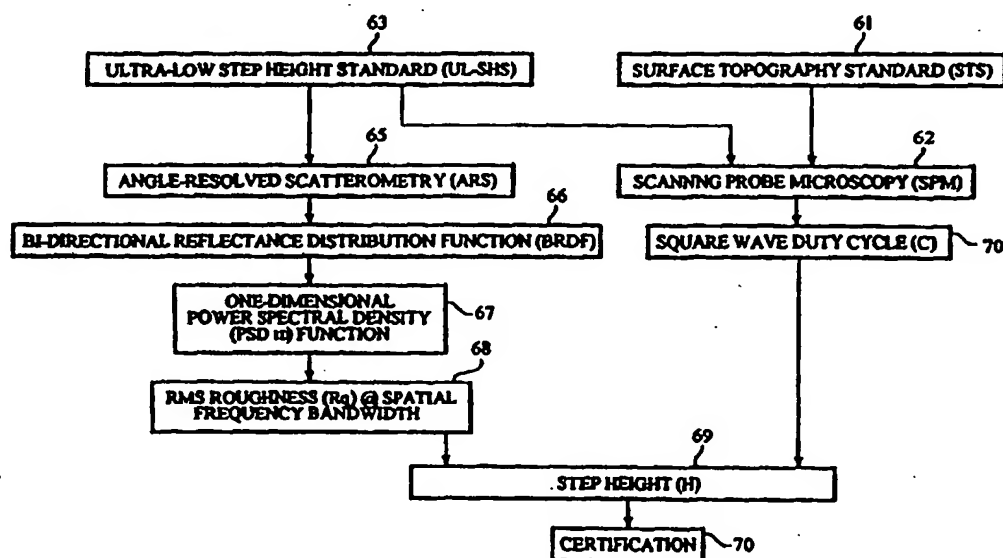
(57) Abstract

Scanning Probe Microscopy (62) is used on a UL–SHS, i.e. Ultra–Low Step Height Standard (63) and a Surface Topography Standard (61) to determine a Square Wave Duty Cycle (C) to be used in step (70). Angle–Resolved Scatterometry (65) is used on UL–SHS (63) to determine a Bi–Directional Reflectance Distribution (66) and thereafter a One–Dimensional Power Density Function (67) and therafter an RMS Roughness @ Spatial Frequency Bandwidth (68). Therefrom and from Square Wave Duty Cycle (C) Step Height (69) is determined and Certification (70) is completed.

Description

ATOMIC–LEVEL STEP–HEIGHT STANDARD CERTIFICATION METHOD

5

TECHNICAL FIELD

The present invention relates to measurement of surface profile of topographic features on generally smooth surfaces, and in particular to measuring the

10 height of step features on such surfaces using any of various mechanical or optical profiling instruments. The invention relates especially to calibration of step-height measuring instruments using a step-height calibration standard and to the certification of such standards.

15

BACKGROUND ART

A step height standard is useful for calibrating surface profiling instruments. One such standard is disclosed by Peter Z. Takacs and Eugene L. Church in an

20 article entitled "A Step-Height Standard for Surface Profiler Calibration" in SPIE Vol. 1995 Optical Scattering (1993), pp. 235-244. That standard includes a flat region with a single central step anisotropically etched therein and also includes two laminar profile bar

25 patterns of 50 μm and 10 μm pitch. The single step is useful for calibrating optical profilers, while the bar patterns are useful for calibrating stylus profilers. The bar pattern ensures that the stylus probe will find an edge on the first try regardless of its lateral posi-

30 tion. The peak-to-valley height of steps are approximately 150 nm.

Recently, techniques have been developed to make smaller scale vertical features. One such method for use in making calibration standards is described in

35 U.S. Pat. No. 5,599,464 to Laird et al., assigned to the assignee of the present invention. With that method, features having vertical heights on the order of 10 Å (1 nm) can be consistently made. The patent further

discloses that millions of such features can be produced simultaneously on a wafer to simulate the effect of haze or microroughness on a polished wafer, and thereby be useful as a microroughness standard.

5   John C. Stover in an article entitled "Requirements and suggestions for industrial smooth surface microroughness standards" in SPIE vol. 2862 Proceedings, 8-9 August 1996, Denver, CO, pp. 69-77, suggests a microroughness standard having a grating with a

10   rectangular cross-section and a 50% duty cycle. With that standard the resulting power spectral density (PSD) is composed of an infinite series of harmonically related peaks (with even orders missing when the duty cycle is 50%) whose amplitudes relate to the height of the grating

15   steps and which fall off as f^{-2}, where f is the spatial frequency related to the pitch of the grating. Moreover, the RMS microroughness value is found by taking the square root of the sum of that series of peaks (out to about the 21st order).

20   In the case of step height standards, it has been found difficult to verify the step height in order to certify the standard when the step heights become less than about 50 Å. For example, when atomic force microscopes are used to measure epitaxial silicon step height

25   directly, the step height value obtained depends on the exact crystal orientation of the wafer and can easily be off by as much as 20%.

It is an object of the present invention to provide a method of certifying a step-height calibration

30   standard with proved traceability and a method of calibrating step-height measuring instruments with the calibration standard certified by the first method.

DISCLOSURE OF THE INVENTION

35   The object is met with a method that makes use of a rectangular-grating type microroughness standard and employs it as a step-height standard instead. The standard is a physical artifact having a generally smooth

reflective surface but with regular features formed on
the surface. These regular features are a periodic
pattern of alternating parallel flat linear mesas and
valleys with a one-dimensional (1D) square-wave

5   (rectangular) cross-section. The characteristic step
height (mesa-to-valley) is at most 100 Å and the period-
icity or pitch (P) of the pattern is less than 100 μm,
and preferably about 20 μm.

The certification method includes measuring the

10 pitch of the periodic pattern of surface features and at
least one of the line width (L) of the mesa features and
the space width (S) of the valleys using a calibrated
probe microscope, such as an atomic force microscope.
From this measurement, a duty cycle (C) of the pattern is

15 derived, where $C = L/P = 1-(S/P)$. Preferably, the
standard being certified has a duty cycle of about 50%.
The certification method further includes use of an
angle-resolved scatterometer to measure a bidirectional
reflectance distribution function (BRDF) for light

20 scattered from the periodic pattern of surface features
on the standard. From this measurement and the derived
duty cycle, the characteristic step height (H) is
ultimately determined by a series of calculations. Those
calculations involve obtaining a 1D power spectral dis-

25 tribution (PSD) function from the measured BRDF values,
then deriving an RMS roughness (R_q) value from the PSD
function, and finally determining the characteristic step
height (H) from the R_q value according to the equation
$H = R_q [C(1-C)]^{-1/2}$. The measurements and calculations

30 should be done over a spatial frequency bandwidth of at
least from $f_{min} \approx 1/(2P)$ to $f_{max} \geq 25 f_{min}$ for sufficient
accuracy of the certified step height value.

Once the step-height calibration standard has
been certified it can be used to calibrate step-height

35 measuring instruments of many types. The standard, now
with known pitch, duty cycle, and characteristic step
height, is placed in the measuring instrument. The step
height of the standard is measured with the instrument to

be calibrated according to the techniques specific to
that instrument, and the measured result is then compared
with the known certified values. As in all calibration
techniques, the comparison is used to make adjustments to
5   the instrument to bring the measured step height value in
line with the certified value. Multiple successive
measurements with intervening adjustments may be needed
to complete the calibration.

        The certification method of the present
10   invention allows standards of much smaller step height to
be certified than previous techniques. In particular,
the invention is a result of a recognition that a prior
microroughness standard has characteristics that
precisely relate measured microroughness via optical
15   scattering to step height of the features on the
standard. Accordingly, this particular type of micro-
roughness standard has been discovered to be useful as a
step height standard as well.

20   BRIEF DESCRIPTION OF THE DRAWINGS
        Fig. 1 is a perspective view of an article used
as a step-height standard in the present invention.
        Fig. 2 is an enlarged perspective view of the
portion of the standard within the area designated by the
25   circle 2 in Fig. 1.
        Fig. 3 is a schematic side view of a cross-
section of the standard of Fig. 1, illustrating the
various parameters, pitch (P), line width (L), space
width (S) and step height (H) measured by the
30   certification method of the present invention.
        Figs. 4A-4F and Figs. 5A-5F are side views of a
wafer step height standard in various stages of manufac-
ture according to two respective manufacturing processes.
        Fig. 6 is a flow diagram showing the steps of
35   the certification process of the present invention for
the standard of Fig. 1.
        Figs. 7 and 8 are, respectively, a schematic
perspective view of the standard and a graph of measured

depth versus frequency of measured occurrences, illus-
trating the intrinsically statistical average nature of
measured step-height.

5   BEST MODE OF CARRYING OUT THE INVENTION
            With reference to Fig. 1, the calibration
     standard is a physical artifact in the form of a silicon
     wafer die 10 having a pattern of regular surface features
     12 formed in the top surface 14 of the die. The die may
10   be approximately 525 μm thick and have major surface
     dimensions of 7 mm by 14 mm. The pattern of surface
     features 12 may occupy a 7 mm by 7 mm area of the top
     surface 14. These dimensions however are not critical
     and should be considered strictly exemplary. The die may
15   be mounted on a larger substrate, such as a 50 mm by 50
     mm by 6 mm thick quartz substrate for use on profilometer
     stages, or could be unmounted for use with atomic force
     microscope (AFM) or other scanning probe microscope (SPM)
     which have limited inspection areas. The die form can
20   thus be selected based upon the substrate handling capa-
     bilities of the instrument to be calibrated.
            Referring to the enlarged view in Fig. 2, the
     regular surface features 12 on the top surface 14 of the
     die are seen to be a periodic pattern of alternating
25   parallel flat linear mesas 16 and valleys 18 with a one-
     dimensional square-wave, i.e. rectangular, cross-section.
     The top surface 14 itself is a generally smooth reflec-
     tive surface but for the steps created by the alternating
     mesas 16 and valleys 18. That is, the tops of the mesas
30   16 are generally planar, smooth and specularly reflec-
     tive, and likewise the surface in the valleys 18 is
     generally planar, smooth and specularly reflective, with
     minimal haze. A thin film of native oxide 19 generally
     forms on the otherwise bare silicon substrate 10.
35   The oxide film 19 should not be removed, since
     a new film will naturally form again, and the surface
     must be stable for the calibration standard to maintain a
     certified step height value. Any cleaning process which

changes the microlevel texture of the standard's surface,
even blowing with a compressed gas, will change the step
height value, such that the standard will require
recertification. Similarly, the standard should not be
exposed to high temperatures that would grow the oxide
film 19, nor should the standard be allowed to get wet.
To prevent particles from contaminating the surface and
diminishing the accuracy of the standard, the standard
should be stored in a container with a class 10 environ-
ment or better, and should only be removed from its
container when ready to perform a calibration measure-
ment, then returned immediately to the container. Care
should be exercised in handling the standard.

Turning now to Fig. 3, the cross-section of the
regular pattern of features exhibits a number of
parameters that can be quantified. Since the pattern is
periodic, it has a periodicity or pitch P which is the
width dimension across mesa-valley pairs. This pitch
dimension P is made up of contributions from the line
width L, which is the width dimension across the mesas,
and the space width S, which is the width dimension
across the valleys. Thus, $P = L + S$. We can also define
a duty cycle (C) from any two of those measured
quantities. $C = L/P = 1 - (S/P) = L/(L+S)$. The final
measurable quantity is the step height H, which is the
depth dimension from the top of the mesas to the floor of
the valleys. As will be discussed further below with
reference to Figs. 7 and 8, the step height is intrinsic-
ally an average value in any actual calibration standard.

. Referring now to Figs. 4A-4F and 5A-5F, two
processes for making the surface features on the wafer
die that form the calibration standard are shown. The
processes are described in U.S. Pat. No. 5,599,464. The
figures show the manufacture of a single feature, but in
practice, all of the features on the wafer would be made
simultaneously.

Fig. 4A shows a silicon wafer 20 having a
uniform layer 21 of silicon dioxide thermally grown onto

the silicon substrate. The silicon dioxide layer has a thickness of between 500 Å and 1000 Å. In the book Silicon Processing for the VLSI Era, vol. 1, p. 200-212, the thermal oxidation of silicon is explained. The book mentions that Deal and Grove described silicon oxidation as proceeding by the diffusion of an oxidant, such as molecular oxygen, through an existing oxide to the silicon-silicon dioxide interface, where molecules react with silicon to form silicon dioxide. In other words, oxygen migrates to the bare silicon substrate, where it interacts with silicon, thereby lowering the level of the silicon/silicon dioxide interface in places where oxidation has occurred. This is a key aspect of the present invention.

In Fig. 4B, a thin layer 23 of positive photo-resist is applied. The photoresist may be patterned with the desired location, areawise extent and overall density of features by means of a mask. When light is used to expose the photoresist layer 23 through the mask, a latent image of the features is formed in the photoresist by light. In other words, the chemical bonds in the exposed photoresist are broken, altering the molecular weight and solubility of the resist, which allows the latent image to be developed, removing the exposed photoresist in the etched area, uncovering the underlying silicon dioxide layer. In the case of positive photo-resist, the bonds of the exposed photoresist are broken.

In Fig. 4C, portions of the resist layer 23, now removed, create an aperture 25 where the resist has been exposed by light. An oxide etchant is used to remove silicon dioxide down to the upper surface 27 of the silicon substrate 20, which is uniformly lower than the original level.

In Fig. 4D, the photoresist is stripped from the oxide layer 21. The aperture region 25, now a single trench 31 in an array of similar trenches which will form topographic features, including the light scattering features of the present invention, undergo self-limiting

reoxidation due to exposure to air. Any oxidizing
ambient environment could be used, but air is effective
and inexpensive. Air oxidation at room temperature
produces native oxide which has a thickness of approxi-
mately 17 Å. Approximately half of the native oxide
layer consumes silicon at the substrate interface. This
is shown in Fig. 4E, where the native oxide at the bottom
of a pit extends into the silicon substrate, below the
former level 27 supporting the silicon dioxide. The
formation of the native oxide layer is rapid, but gene-
rally stops by itself after a short time.

Next, all of the oxide is stripped, as shown in
Fig. 4F. It is now apparent that a differential step
height exists between the bottom of the trench 33 and the
former base 27 which supported the silicon dioxide.

In Figs. 4A-4F, the construction of a topo-
graphic feature has been shown using a dark field mask,
resulting in a pit 33 within a light reflecting field 27.
A reverse process could be used, producing a mesa feature
having a step height, rather than a trench. The reverse
process could be achieved with reverse masks or with
photoresist of the opposite type. This reverse process
is illustrated in Figs. 5A-5F.

In Fig. 5A, a uniform thermal oxide layer 41 is
grown on a polished, light-reflective silicon wafer to a
thickness which is between 700 Å and 1000 Å. Such layers
are readily produced in the semiconductor industry with
good consistency and uniform thickness over the surface
of a wafer. Lesser thicknesses could be produced, but
the range of 700 Å to 1000 Å is preferred because of the
ease of manufacturing and of verifying the thickness with
measuring instruments.

In Fig. 5B, a layer of photoresist 43 is
disposed over the thermal oxide layer 41. The photo-
resist is exposed to light through a mask which is the
optical complement of the mask used for the exposure
previously described with respect to Figs. 4B and 4C.

After removing the exposed portions of the photoresist and etching the oxide, a mesa is left, as shown in Fig. 5C. The mesa 45 consists of a small layer of photoresist 43 atop a similarly sized layer of thermal

5   oxide 41. In Fig. 5D, the photoresist portion is shown to be stripped away.

In Fig. 5E, a very thin layer of native oxide 51 grows on the exposed silicon as air is allowed to be in contact with the wafer, consuming silicon below the

10   initial wafer level. The silicon dioxide island 41 is removed, leaving a small mesa or feature 53, which also is exposed to air and has a uniformly thin native oxide layer. The feature 53 extends approximately 8 Å to 9 Å above the surface of the surrounding silicon field.

15   With reference to Fig. 6, certification of the standard is based primarily on a measurement of rms microroughness (R_q) that is traceable to physical first principles analysis. For a one-dimensional square-wave (rectangular) cross-section and a 50% duty cycle for the

20   pattern features, the step height H is equal to 2 R_q. This relationship has to be modified slightly when the duty cycle is not exactly 50%, but essentially the characteristic step height of this particular standard is derivable from angle-resolved scatterometry measurements.

25   For accuracy, the scatterometry measurement is supple- mented by an atomic force microscope (or other scanning probe microscope) measurement of pitch and line widths to obtain the duty cycle of the pattern. Although atomic force microscopes have been found unsuitable for certi-

30   fication purposes of direct step height measurement of ultra-low step features (H ≤ 50 Å), they are capable of accurate measurement of the pitch, line and space widths, which are typically on the order of about 5 μm to 50 μm wide.

35   Beginning with the duty cycle determination, the scanning probe microscope (SPM), such as an atomic force microscope, is first calibrated for accurate width measurement by means of a surface topography standard

(STS) 61. That standard is traceable to NIST SRM-476.
Once the SPM has been calibrated, it is used to measure
(step 62) the pitch (P) line and space widths (L and S)
of the features on the ultra-low step height standard

5   (UL-SHS) 63 to be certified. From any two of these
measurements, the duty cycle (C) is derived (step 64)
according to the definition $C = L/P = 1-(S/P)$, where P =
L + S is the pitch and L and S are the line widths of the
mesa features and space widths of the valleys, respec-

10   tively.

Next, the microroughness value R_q is measured by
means of optical scatterometry. In particular, angle-
resolved scatterometry (step 65) is employed to obtain a
bi-directional reflectance distribution function (BRDF)

15   66 for light scattered from the periodic pattern of
surface features. Specifically, the periodic pattern
acts as a kind of grating that scatters light in certain
preferential directions, with the intensity of the
various scattering directions dependent upon the pattern

20   dimensions, including the step height H. An illumination
laser beam with a 3 mm diameter spot size on the standard
and a 633 nm wavelength is typical for a scatterometer.
From the measured BRDF, a one-dimensional power spectral
density (PSD_{1D}) function is calculated (step 67), and from

25   that PSD_{1D} function the rms roughness (R_q) value is
derived (step 68). The measurement and calculations are
preferably carried out for a spatial bandwidth of at
least from a minimum spatial frequency $f_{min} \approx 1/(2P)$ to a
maximum spatial frequency $f_{max} \geq 25\, f_{min}$, in order to

30   capture at least out to the 11th order odd harmonic of
light scattering. Preferably, $f_{max} \approx 1.2\ \mu m^{-1}$, which for
a typical pitch P of about 20 μm well exceeds the 25 f_{min}
lower limit for f_{max}. The minimum spatial frequency f_{min} is
selected simply to ensure that it captures the funda-

35   mental order of light scattering at spatial frequency $f_1 =$
$1/P$. The traceability of the R_q measurement is traceable
to intrinsic standards set forth in ANSI/NCSL ZS40 and
ISO 10012.

The calculation of rms microroughness R_q by
means of optical scatterometry measurements on a standard
having the above-described periodic pattern of surface
features is described in copending U.S. patent applica-
tion no. 08/908,524, filed August 7, 1997, assigned to
the assignee of the present invention. Briefly, the
scatterometry instrument may be a TMA CASI(r) angle-
resolved light scattering (ARS) instrument. This is a
specialized tool that allows for first-principles trace-
ability based on the wavelength of light and optical
geometries of the instrument. The actual quantity
measured through angle-resolved scatterometry is the bi-
directional reflectance distribution function (BRDF),

$$(1) \qquad BRDF = \frac{P_s \; / \; \Omega_s}{P_i \cdot \cos \theta_s} \qquad ,$$

where P_s is the power of the scattered light collected
over the solid angle Ω_s as a function of the angle θ_s.
The factor P_i indicates the incident laser power at angle
θ_i from the wafer normal. Therefore, BRDF is physically
nothing more than the redistributed energy scattered into
a given solid angle.

In the case of a laser based instrument, such
as an integrating scatterometer, the bandpass is defined
as follows. If the incident monochromatic laser beam, at
incidence angle θ_i , specular beam and scatter beams (at
angles θ_s) are all in the same plane, the spatial
frequency is related to the scatter angle by the one-
dimensional grating equation

$$(2) \qquad f = \frac{\sin \theta_s \cdot \cos \phi_s - \sin \theta_i}{\lambda} \qquad ,$$

where f is the spatial frequency and λ is the laser
illumination wavelength. The ϕ_s term takes on values of
1.0 and -1.0 for ϕ_s = 0° and 180° respectively.

Ideally, the instrument transfer function is
flat in the bandpass region and zero elsewhere. This is
never achieved in practice and the spatial bandpass must
always be convolved with the transfer function (if
available) in order to achieve true inter-instrument
comparisons.

The one-dimensional power spectral density
(PSD) function is a measure of the scattered power per
unit of spatial frequency f. The PSD function is
calculated from the measured BRDF:

$$(3) \qquad PSD(f_x, f_y) = \frac{10^8 \lambda^4 \quad BRDF}{16\pi^2 \cdot \cos \theta_s \cdot Q} \qquad ,$$

where, for s-polarization, the factor Q is approximated
by the specular reflectance of the wafer surface. The
reflectance is a function of wavelength, incidence angle,
and polarization. If the surface is isotropic, PSD(f_x,
f_y) may be integrated around the azimuthal angle ϕ_s to
obtain an isotropic PSD function

$$(4) \quad PSD_{iso}(f) = \int_0^{2\pi} PSD (f_x, f_y) f \, d\phi_s \quad = \quad 2\pi f \cdot PSD (f_x, f_y)$$

with units of $Å^2\mu m$ and f equals the root-sum-of-squares of
f_x and f_y. It is this function, $PSD_{iso}(f)$ in equation 4,
that is added to the one-dimensional PSD function and
becomes the function from which rms roughness is calcu-
lated. The square wave is a one-dimensional scatterer,
however, the roughness of the silicon "peaks and troughs"
are isotropic scatterers. Therefore, two measurements
are made -- one with the direction of the square wave
surface perpendicular to the plane-of-incidence of the

-13-

laser (for the overall one-dimensional PSD curve genera-
tion), and one where the surface is parallel. The second
scan measures the silicon roughness, independent of the
etched features. This value is then converted to an
isotropic value, equation 4, and then added as the root-
sum-of squares to the one-dimensional scan (equation 7).
The silicon roughness is really only significant at low
nominal roughness values but is consistently measured as
a matter of practice.

The PSD function is the frequency spectrum of
the surface roughness measured in units of spatial
frequency, typically inverse micrometers. The PSD
function provides information about both the amplitude
and spatial wavelength $(1/f)$ of the surface. The rms
roughness may be calculated directly as the square root
of the integral of the one-dimensional PSD curve. In the
case of the rms microroughness standard, an isotropic
roughness value needs to be added in as well to account
for the inherent roughness of the silicon. The rms
roughness, R_q, between spatial frequencies f_{min} and f_{max},
from a one-dimensional power spectral density function,
PSD_{1D}, is

$$(5) \qquad R_q = \sqrt{2 \cdot \int_{f_{min}}^{f_{max}} PSD_{1D}(f)\,df}$$

Since all of the data from angle-resolved
scatterometry are binned into discrete points, the
"integration" required to turn these data into a rms-
roughness value merely becomes the square root of the
summation of the one-dimensional PSD function, $PSD_{1D}(f)$,
multiplied times the differential frequency step size
within the appropriate limits of integration.

$$(6) \qquad R_q = \left(2\int_{f_l}^{f_h} PSD_{1D}(f)\,df \right)^{1/2} \;\Rightarrow\; R_q = \sqrt{2 \sum_{i=f_l}^{f_h} PSD_{1D}\;\;\delta f}$$

-14-

Note also that the equation signifies the limits of
integration denoted f_l and f_h which are set according to
the spatial bandwidth limits of the instrument under
test. To account for the inherent isotropic roughness of
the silicon, we also need to add in an additional term
PSD_{iso} to equation 6. The final formula for the RQS
standard takes the form of equation 7.

(7)
$$R_q = \left(2\int_{f_l}^{f_h} PSD_{1D}(f)df + \int_{f_l}^{f_h} PSD_{iso}(f)df \right)^{1/2}$$

This is the equation that is used to certify a rms-
roughness value for the standard for a given range of
integration limits.

Once both the duty cycle C and the microrough-
ness value R_q from a one-dimensional power spectral
density function (PSD_{1D}) are known (equation 6), the
characteristic step height H of the features on the
standard is determined (step 69) according to the
equation: $H = R_q [C(1-C)]^{-1/2}$. The standard is certified
(step 70) as having the determined step height H and duty
cycle C for use in subsequently calibrating step height
measuring instruments.

Calibration comprises placing the certified
step height standard into step height measuring relation
to an instrument, such as an atomic force microscope or
other scanning probe microscope, interferometer or other
optical profilometer. After measuring the step height
with the instrument, either directly or through a series
of calculations from indirect measurements, the resulting
measured value is compared against the known certified
value of the step height H. Any deviations of the
measured value obtained from the instrument to be
calibrated to the known certified value are used to
adjust the instrument until the measured and certified
values are equal within certified uncertainty.

With reference to Figs. 7 and 8, the definition
of the characteristic step height H is necessarily an
effective or mean step height due to the intrinsic
surface texture of the standard itself. The etched
5   silicon substrate's surface has a thin film of native
oxide (as seen in Fig. 2). The oxide film is an
amorphous silica (SiO_2) with a nominal molecular
"diameter" of about 3.55 Å. Even the best standard would
have this amorphous silica film which produces
10. microtextured mesa and valley surfaces 72 and 74. The
dots shown in Fig. 7 represent the amorphous silica
"molecules". Due to the very low levels of surface
texture provided by the features (a typical step height H
is about 10 Å, which is only 2.8 times the nominal silica
15   "diameter"), any step height measurement is necessarily
statistical in nature. Fig. 8 illustrates the height or
depth Z of various portions of the mesa and valley
features. The number of occurrences N of a particular
depth measurement is plotted versus the depth Z, and
20   shows a (bell-shaped) Gaussian distribution about a mean
$\overline{Z}$ for both the mesas and valleys. The first curve 76
represents depth measurements for various parts of the
valleys and has a mean $\overline{Z}_{bottom}$. The second curve 78
represents corresponding depth measurements for various
25   parts of the top surface of the mesa features and has a
mean $\overline{Z}_{top}$. The step height H is a mean value $\overline{H}$ that is:

$$\overline{H} = \overline{Z(x,y)}_{top} - \overline{Z(x,y)}_{bottom} \text{, where measurements are}$$

30   averaged over surface positions (x,y). Note that the
statistical nature of the feature depths occurs even when
all of the mesas 72 have identical average depths $\overline{Z}_{top}$ and
all of the valleys 74 likewise have identical average
depths $\overline{Z}_{bottom}$. Height variations between different
35   features are also possible and are averaged out by the
scatterometry measurements with the 3 mm diameter illumi-
nating laser spot, which encompasses parts of about 300
different mesa and valley features.

Claims

1.   A method of certifying a step height calibration
standard, said standard being a physical artifact having
a generally smooth reflective surface but with regular
features formed on said surface, said regular surface
features being a periodic pattern of alternating parallel
flat linear mesas and valleys with a one-dimensional
square-wave cross-section, said pattern of alternating
mesas and valleys having a periodicity or pitch of less
than 100 μm, a duty cycle known to be approximately 50%
and a characteristic step height of at most 100 Å, said
method of certifying comprising the steps of:
       measuring a bi-directional reflectance
distribution function (BRDF) for light scattered from
said periodic pattern of surface features using an angle-
resolved scatterometer, and calculating an rms roughness
(R_q) value from said BRDF measurement; and
       determining said characteristic step height (H)
of said pattern of features on said standard from said
calculated R_q value and an assumed 50% duty cycle, said
standard being certified as having said regular surface
features with said determined characteristic step height
(H) for use in subsequently calibrating step height
measuring instruments by means of said certified
standard.

2.   The certification method of claim 1 further
comprising:
       measuring said pitch (P) of said periodic
pattern of surface features and at least one of a line
width (L) of said mesas and space width (S) of said
valleys using a calibrated probe microscope, and
verifying a duty cycle (C) of said pattern from said
measurements, where C = L/P = 1-(S/P), said standard
further being certified as having said pattern of surface
features with said verified duty cycle (C), said determi-

nation of characteristic step height (H) being according to the equation: $H = R_q \left[C(1-C) \right]^{-1/2}$.

5   3.   The certification method of claim 2 wherein said probe microscope is an atomic force microscope calibrated with a surface topography standard traceable to published NIST SRM-476.

10

4.   The certification method of claim 2 wherein said pitch (P) is about 20 μm.

15   5.   The certification method of claim 2 wherein said duty cycle (C) is about 50%.

6.   The certification method of claim 1 wherein said R_q
20   value is derived from a one-dimensional power spectral density (PSD) function that is calculated from said BRDF measurement.

25   7.   The certification method of claim 1 wherein said R_q value is obtained over a spatial frequency bandwidth of at least from $f_{min} \approx 1/(2P)$ to $f_{max} \geq 25 \ f_{min}$.

30   8.   The certification method of claim 1 wherein said scatterometer directs an incident laser beam with a diameter of about 3 mm onto said periodic pattern.

35   9.   The certification method of claim 1 wherein said physical artifact constituting said standard is a silicon wafer die.

10. The certification method of claim 9 wherein said die is mounted on a larger substrate.
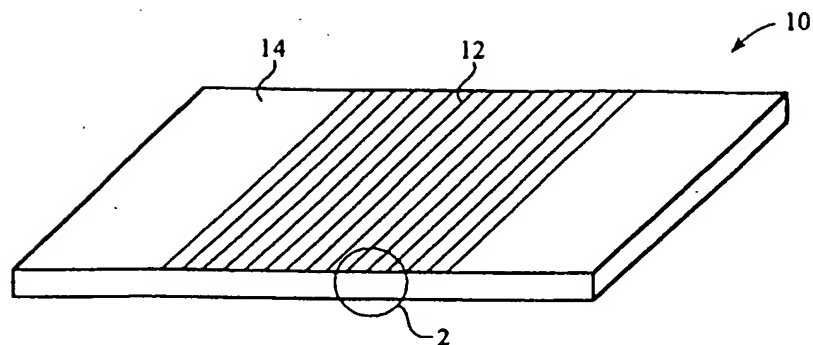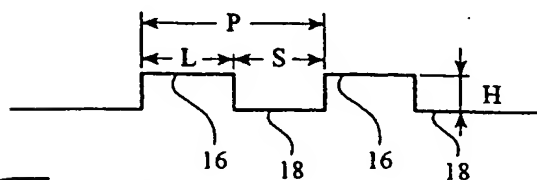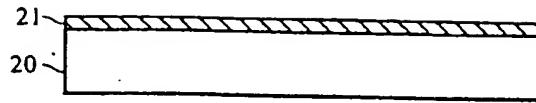
Fig. 1
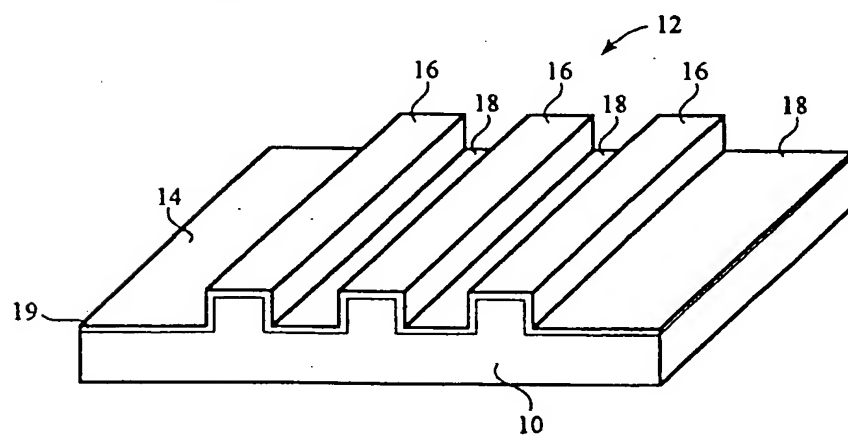
Fig. 2

Fig. 3

Fig. 4A
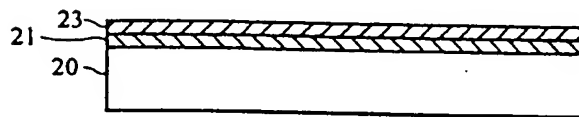
Fig. 4B
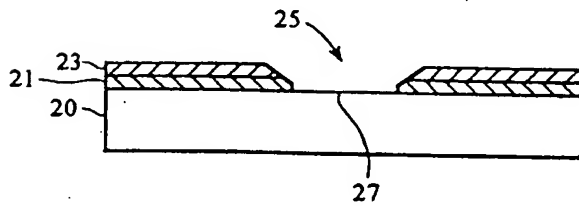
Fig. 4C
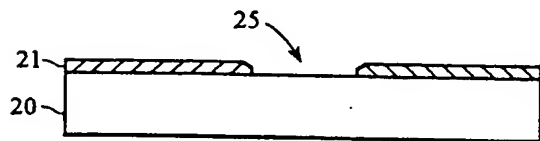
Fig. 4D
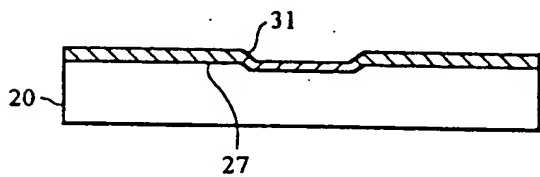
Fig. 4E
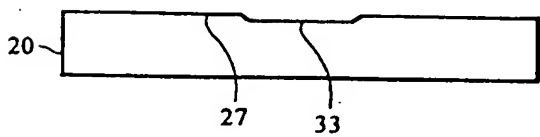
Fig. 4F
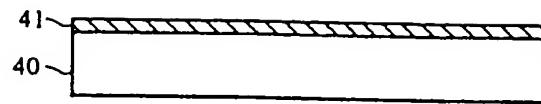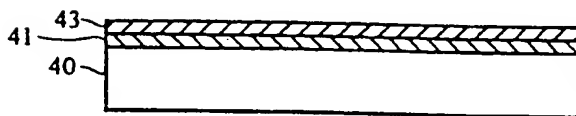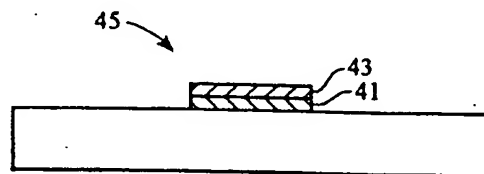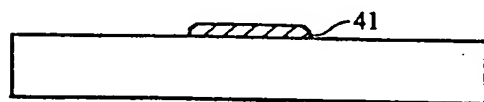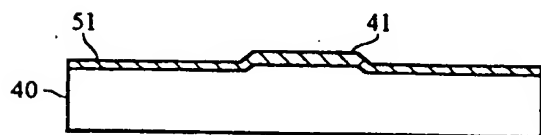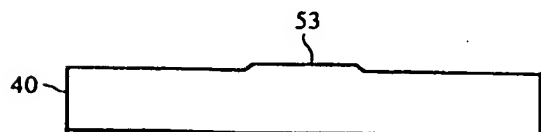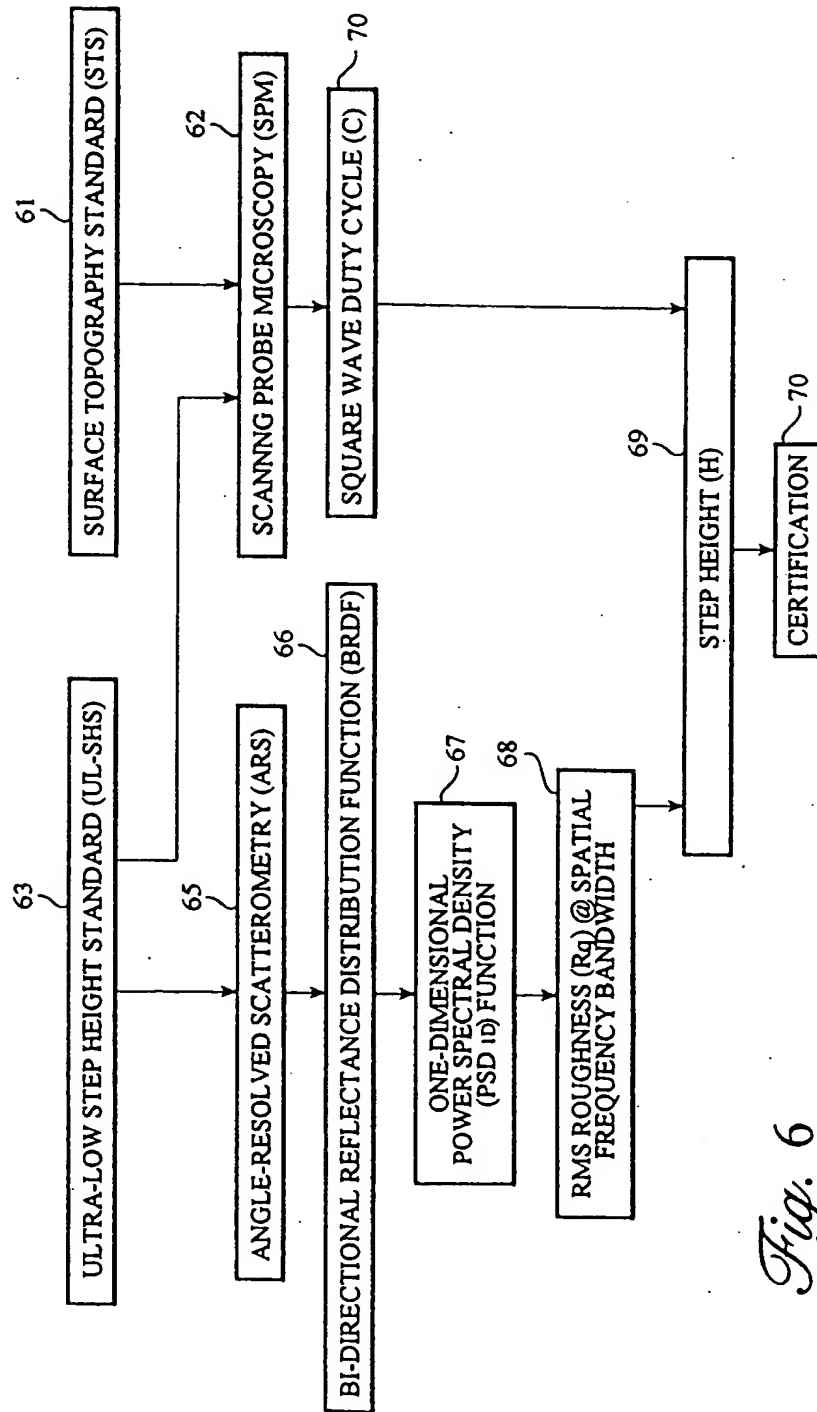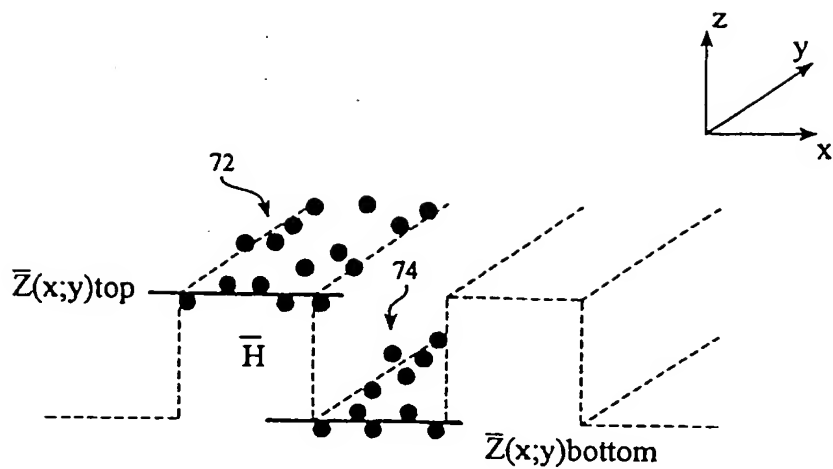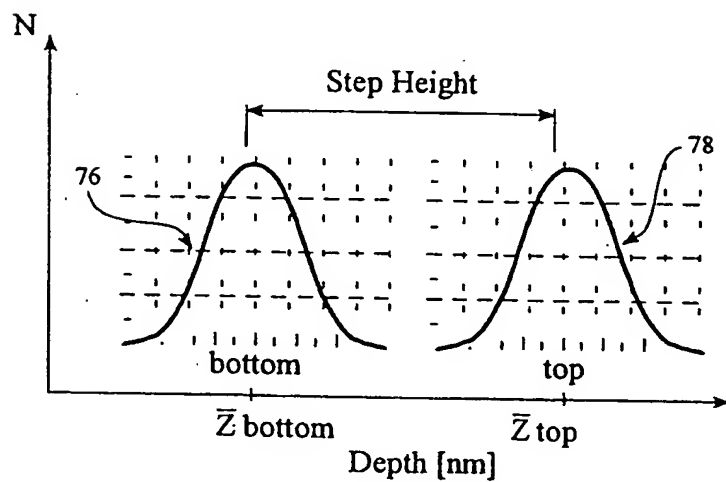
41 —
40 —

Fig. 5A

43
41 —
40 —

Fig. 5B

45

43
41

Fig. 5C

41

Fig. 5D

51   41
40 —

Fig. 5E

53
40 —

Fig. 5F

SURFACE TOPOGRAPHY STANDARD (STS) — 61

SCANNNG PROBE MICROSCOPY (SPM) — 62

SQUARE WAVE DUTY CYCLE (C) — 70

ULTRA-LOW STEP HEIGHT STANDARD (UL-SHS) — 63

ANGLE-RESOLVED SCATTEROMETRY (ARS) — 65

BI-DIRECTIONAL REFLECTANCE DISTRIBUTION FUNCTION (BRDF) — 66

ONE-DIMENSIONAL POWER SPECTRAL DENSITY (PSD 1D) FUNCTION — 67

RMS ROUGHNESS (Rq) @ SPATIAL FREQUENCY BANDWIDTH — 68

STEP HEIGHT (H) — 69

CERTIFICATION — 70

Fig. 6

$$\overline{Z}(x;y)top$$

$$\overline{H}$$

$$\overline{Z}(x;y)bottom$$

Fig. 7

N

Step Height

bottom

top

$$\overline{Z}\ bottom$$

$$\overline{Z}\ top$$

Depth [nm]

Fig. 8

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :G01B 11/30
US CL :73/1.89; 250/252.1; 356/243.4
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
U.S. : 73/1.89; 250/252.1(both unofficial breakdowns R and A); 356/243.4, 243.3, 243.7, For.106

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Please See Extra Sheet.

C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y --- A	TAKACS. P.Z. et al. A Step-Height Standard for Surface Profiler Calibration, SPIE. pub. 1993. Vol. 1995. pages 235-244, especially page 235	1, 6-10 --- 2-5
Y	STOVER. J.C. Requirements and suggestions for industrial smooth surface microroughness standards. SPIE. Proceedings. 8-9 August 1996 (08-09.08.96). Vol. 2862. pages 69-77, especially pages 69-70 and page 74, last paragraph	1, 6-10
Y	US 5,599,464 A (LAIRD et al) 04 February 1997 (04.02.97), abstract, col. 5, lines 31-40 and col.5, line 58 - col. 6, line 27	6, 8-10

[X] Further documents are listed in the continuation of Box C.	[ ] See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 MAY 1999	28 MAY 1999
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer TOM NOLAND Telephone No. (703) 305-4765

Form PCT/ISA/210 (second sheet)(July 1992)*

International application No.

PCT/US99/05189

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,E,L	Abstract of WO 99-08524 A (VLSI STANDARDS INC) 18 February 1999 (18.02.99) , i.e. abstract by DERWENT INFORMATION LTD. copyright listed as 1998 but should apparently be 1999. DERWENT-WEEK: 199916. DERWENT-ACC-NO: 1999-180529	1, 6-10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/05189

B. FIELDS SEARCHED
Electronic data bases consulted (Name of data base and where practicable terms used):

APS: files USPAT, USOCR, EPO, JPO
search terms: certify?, certifie?, certification#, test?, check?, verif?, stepheight#, step, height#, roughness?, microroughness?, calibrat?, reference, standard#